PHYS 393
Low Temperature Physics
Set 2:

Liquid Helium-4

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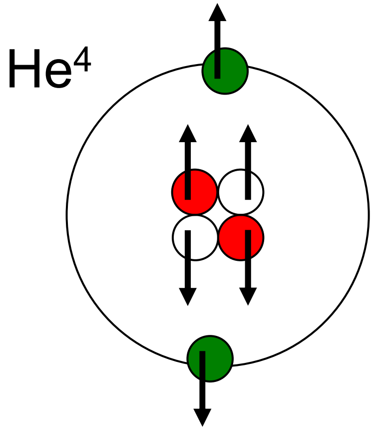
He^4 atom

- Two protons, two neutrons in nucleus: I=0
- Two electrons in K shell ($1s^2$): J=0
- F=0: boson



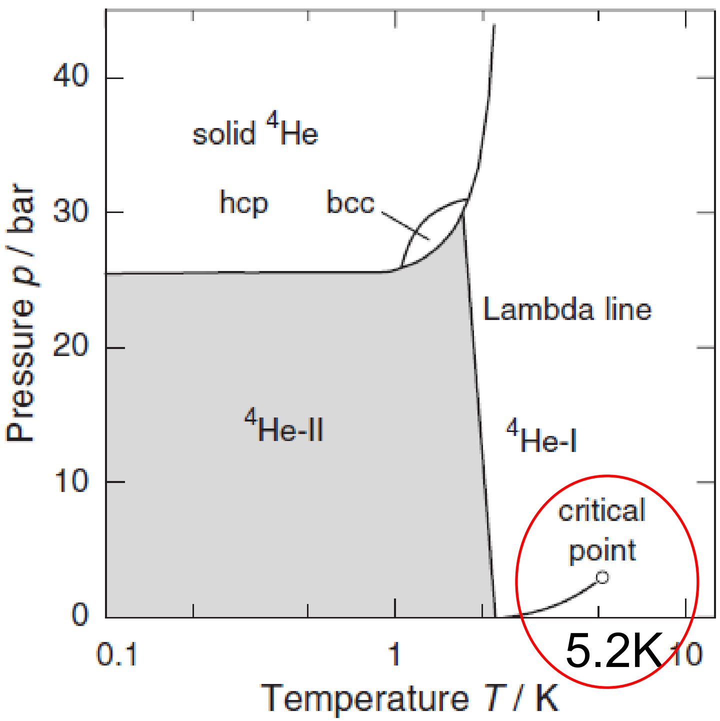
Helium 4

- Normal liquid: 2.17K<T<5.2K
  - boiling point: 4.2K
- Superfluid: T<2.17K (P=1atm)
- Superfluid: T<1.9K (at melting curve)

- Phase diagram (state of He^4 as function of pressure and temperature): under atmospheric pressure liquid down to T=0. No triple point (where gas, liquid, solid co-exist)
- Near T=0 solidifies for P>25atm

- He-I: normal fluid
- He-II: superfluid

Helium 4 phase diagram



He^4 phase diagram

At normal pressure Z.P.E. is always larger than VdW binding energy, hence He^4 remains liquid even at T=0

Flat solid/liquid transition (melting) line for 0<T<2K

No nuclear spin disorder (I=0)

Clausius-Clapeyron for $S_l \approx S_S \approx 0$:

$$\frac{dP}{dT} = \frac{S_l - S_S}{V_l - V_S} \approx 0$$

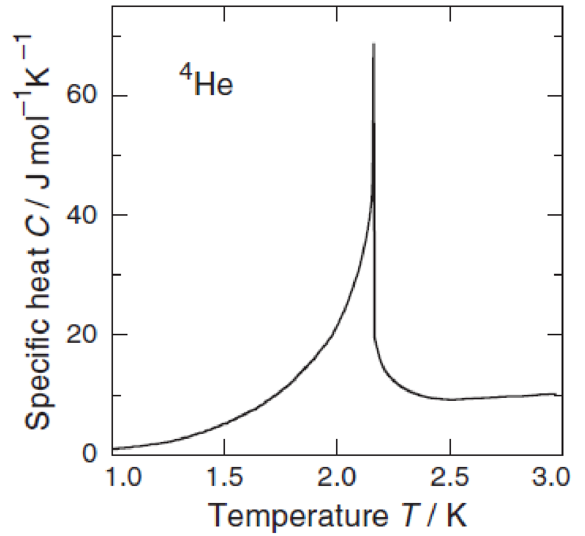
There is a shallow minimum at T=0.8K (not visible on plot scale)

(Very small) entropy of liquid and solid determined by thermal excitations in this T range

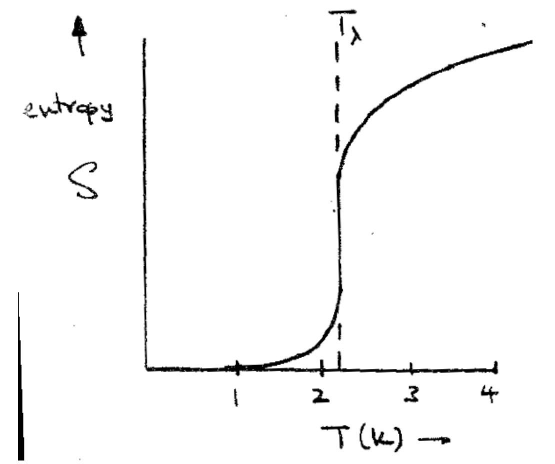
"Phonon anomaly": below 0.8K solid He^4 has larger entropy than liquid He^4

Heat Capacity (C_V, specific heat)

- Abnormal rise of C_V around T=2K observed in 1923
- Pronounced maximum at 2.17K observed and reported in 1932, attributed to phase transition



- He-I for T>2.17K (normal liquid)
- He-II for T<2.17K (zero viscosity): superfluid



- Shape of curve (like Greek λ): lambda-transition
- Steep change in entropy on transition

$$C_V = T\frac{dS}{dT}$$

He-II: experimental observations

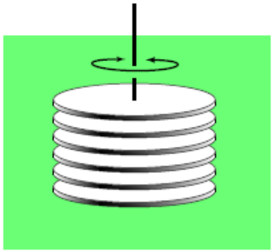
- He-I boils like normal liquid with bubbles rising through its volume
- Below 2.17K it suddenly becomes quiet with evaporation only from the surface

- Flow measurements through thin capillaries and superleaks: viscosity drops at phase transition by orders f magnitude
  - Flow velocity almost independent of pressure gradient
  - Flow velocity increases with decreasing capillary diameter
- Persistent-flow experiments: set into rotation torus filled with compressed fine powder and He-I; lower T below 2.17K; stop rotation of torus; He-II angular velocity stays constant for hours
- Outcome: viscosity drop at phase transition by >11 orders of magnitude

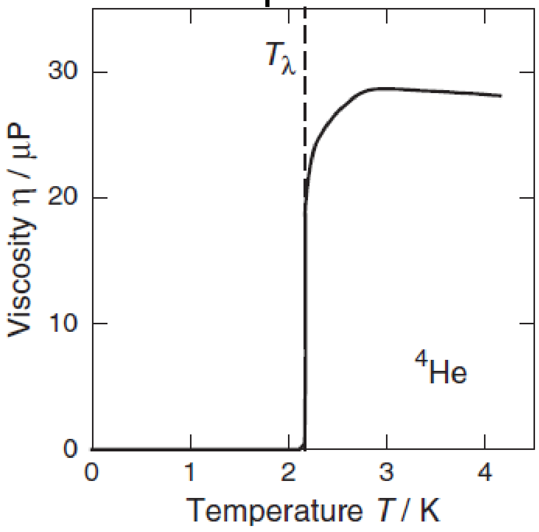
- Behaves as if (part of) the liquid has zero viscosity

He-II: experimental observations

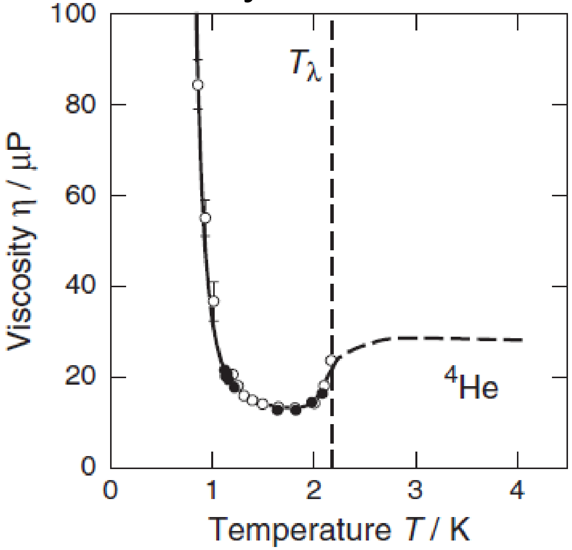
- Viscosity measurements with rotating viscosimeter and oscillating discs measure larger viscosity values, but still below those of He-I



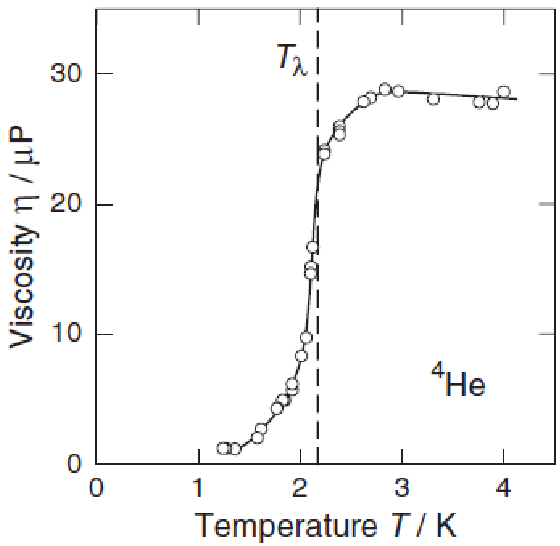
Thin capillaries



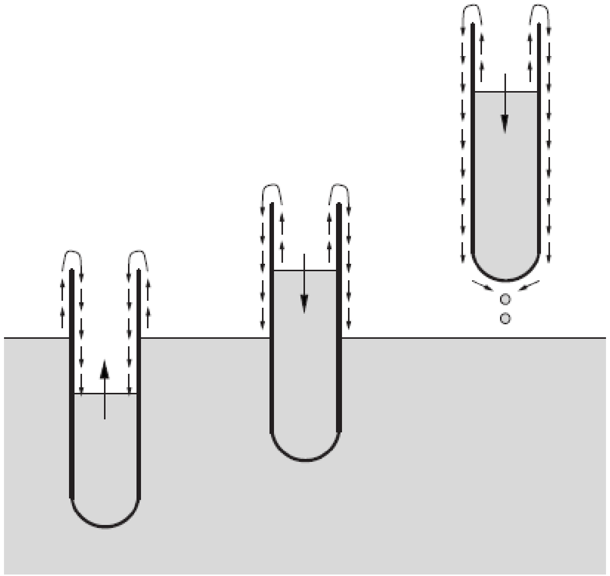
Rotary viscosimeter



Oscillating discs



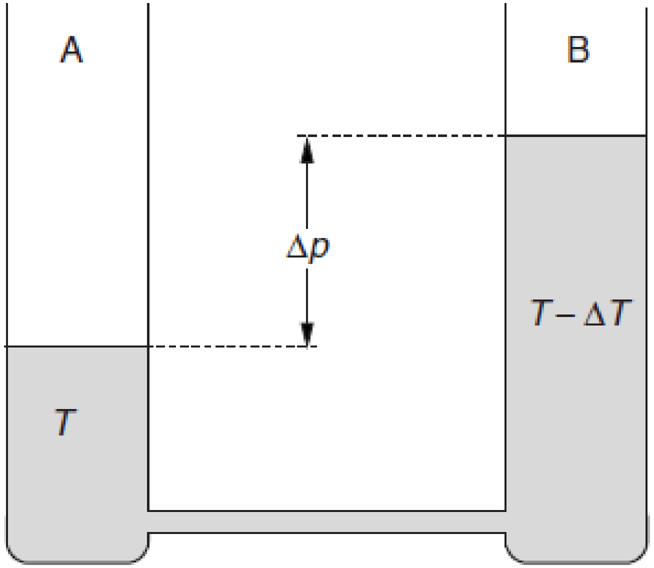
He-II: experimental observations



He-II flows through liquid film on beaker wall until levels outside and inside the beaker are equal

- Left: He-II flows into beaker
- Middle: He-II flows out of beaker

Right: He-II flows out of beaker until beaker is empty



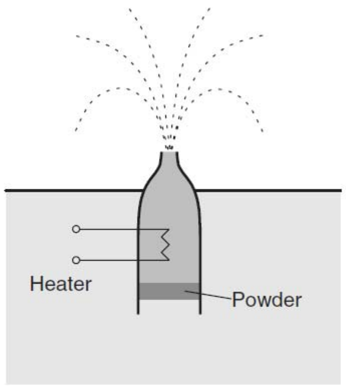
Thermomechanical effect:

A,B contain He-II; connected with very thin capillary

Start with same levels, apply pressure in A: liquid level rises on B and T drops in B, rises in A

Heat flow and mass flow with opposite directions

The fountain effect



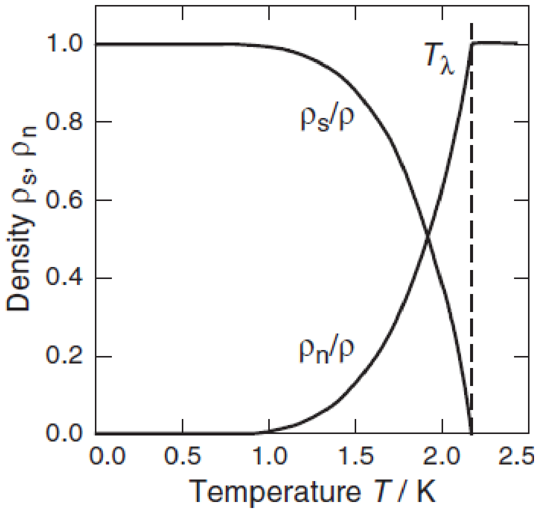
- Thin-neck flask immersed in He-4 at T<2.17K
- Fine compressed powder (superleak) in flask, open bottom
- Heating of the Helium in the flask results in He fountain

Sound in He-II

- Sound waves (alternating regions of high and low atomic density) can pass through liquid He-II
- Waves of higher-lower temperature (generated by electric heater running on low frequency AC) propagates through liquid: second sound
- Third sound: waves in films
- Fourth sound: waves in capillaries

Landau Two-Fluid Model

- He-II behaves as if it were a mixture of two interpenetrating, non-interacting fluids with different properties. One normal, one superfluid. Just a model: two fluids cannot be separated, all He^4 atoms identical, cannot assume there are two types of them in the liquid at the same time



- Total density is the sum of the two components: $\rho(\text{total}) = \rho_n + \rho_s$
- At T=0 all liquid is superfluid (ρ_n=0)
- At T=2.17K all liquid is normal (ρ_S=0)
- Superfluid component carries no entropy, exhibits no viscous friction, and no turbulence can be created in it
- Normal component carries all entropy and has finite viscosity

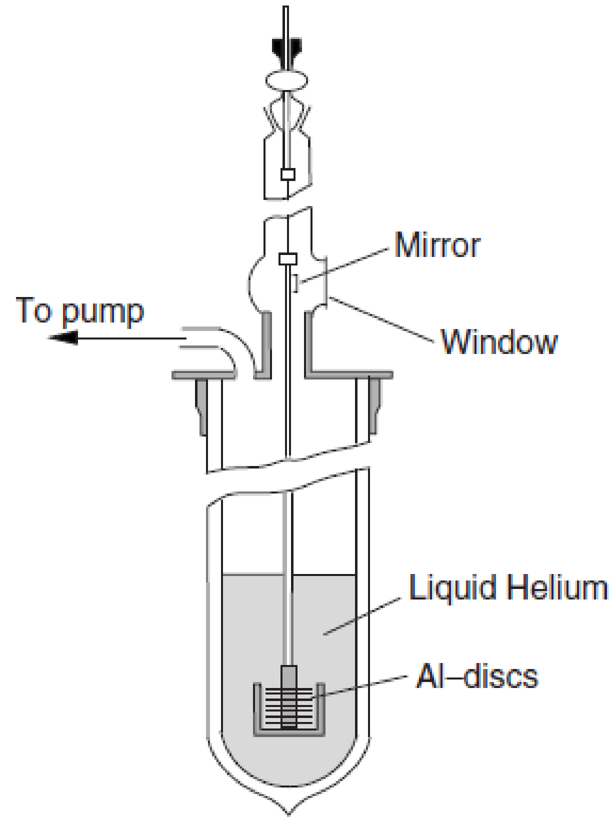
	density	viscosity	entropy
normal-fluid component	ϱ_n	$\eta_n = \eta$	$S_n = S$
superfluid component	ϱ_s	$\eta_s = 0$	$S_s = 0$

Applications of the two fluid model

- Flow through thin capillaries: normal fluid blocked, superfluid flows freely. Motion frictionless, hence zero viscosity
- Rotary viscosimeter: hollow concentric cylinders immersed in liquid. Viscosity determined via the torque between the cylinders. Superfluid liquid applies no torque, "see" only the normal liquid
- Oscillating disc: normal component provides damping. Experiment measures the product of density times viscosity

Andronikashvili's experiment (1948)

- Pendulum: 50 Alu disks, thickness 13μm.
- Disk separation: 210μm.
- Disks "drag" the liquid (for He^4 the normal liquid only) between them which modifies the rotation frequency.
- Measures ρ_n



Thermomechanical effect

- Only superfluid flows through capillary.
- So superfluid mass at T=0 moves to one container
- Results in cooling of the receiving container and in heating the source container
- Warming He-II: in order to keep equilibrium in normal – superconducting components, superfluid flows into heated area: fountain effect

Sound

- Normal sound: propagation of high/low atomic density (total, both normal and superfluid)

- Second sound: propagation of regions of (high superfluid - colder) and (low superfluid - warmer). Seen as temperature change wave.

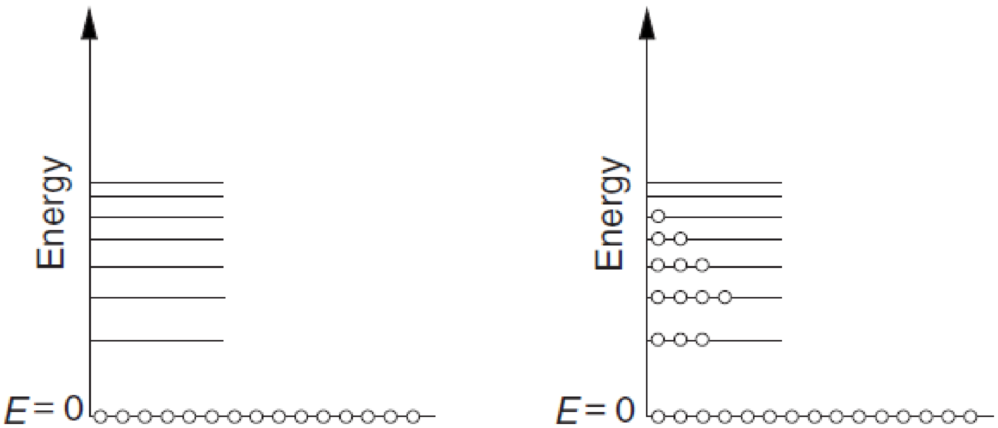
Bose-Einstein Condensation

F. London (1938): Superfluid component in He^4 has a macroscopic wavefunction due to Bose-Einstein condensation:

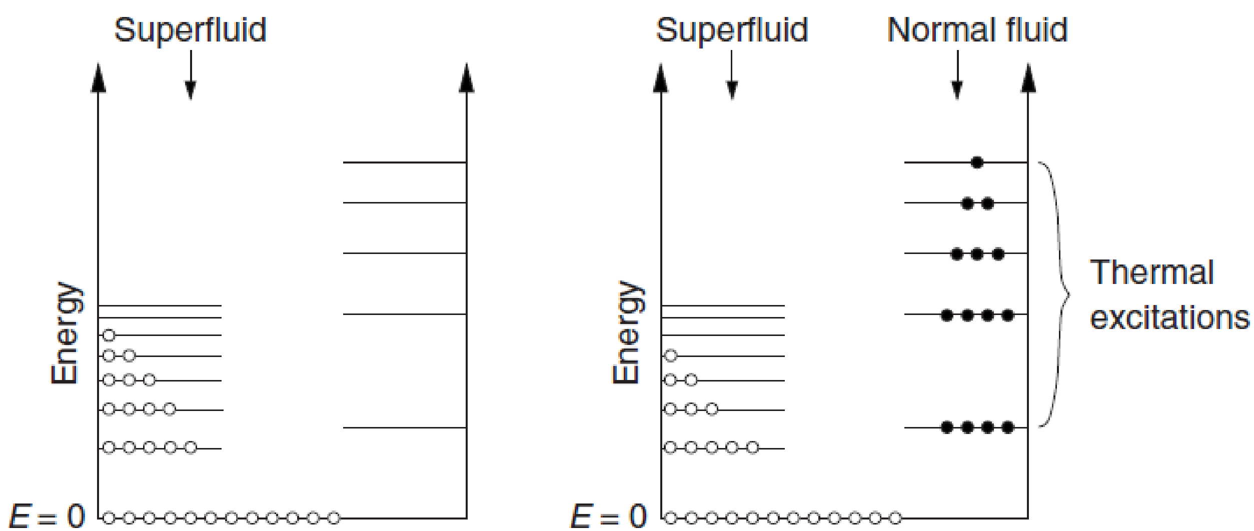
- Superfluid component: B.E. ground state condensate
- Normal component: thermal population of Bose-Einstein excited states
- Transition temperature: $T_B=\lambda$

(see Wolski part 5, pages 28-29)

The two fluid model in terms of B.E.C.



Population in energy levels in ideal Bose gas: Left: T=0, Right: $0<T<T_C$



Population in He-II, Left: at T=0 all liquid is superfluid, some atoms in states E>0 due to interactions. Right: at $0<T<T_C$ thermal excitations constitute normal liquid

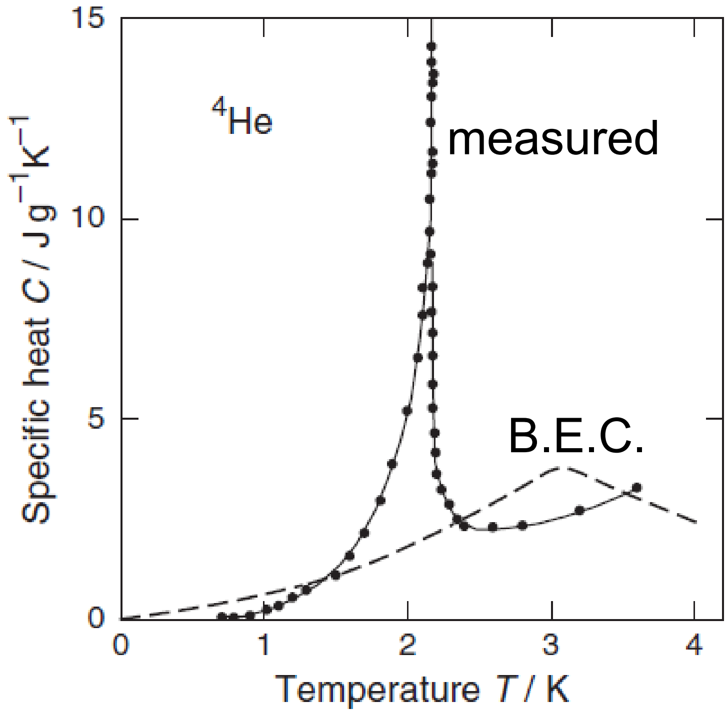
B.E.C. assumption success

- Explains the presence of two components
- Condensate (B.E.C.) has no entropy, behaves as if at T=0 (thermomechanical effect, fountain effect)
- Using experimental value for (V/N) in He^4 and B=1 in formula 34 (Wolski part 5 page 19) we find

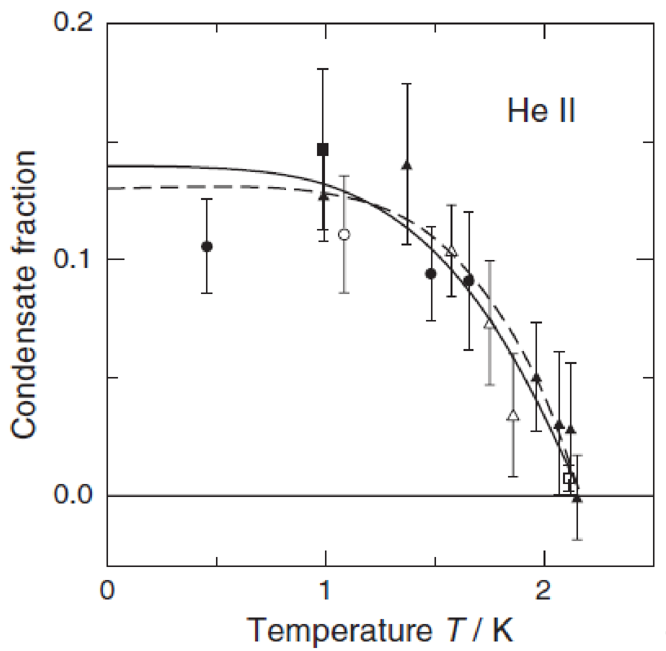
$$T_B=3.1K, \text{ close to } T_\lambda=2.17K$$

Problems of B.E.C. model

- Heat capacity: sharper peak in data (points-line) than theory (dotted line) (see Wolski part 5 page 39)

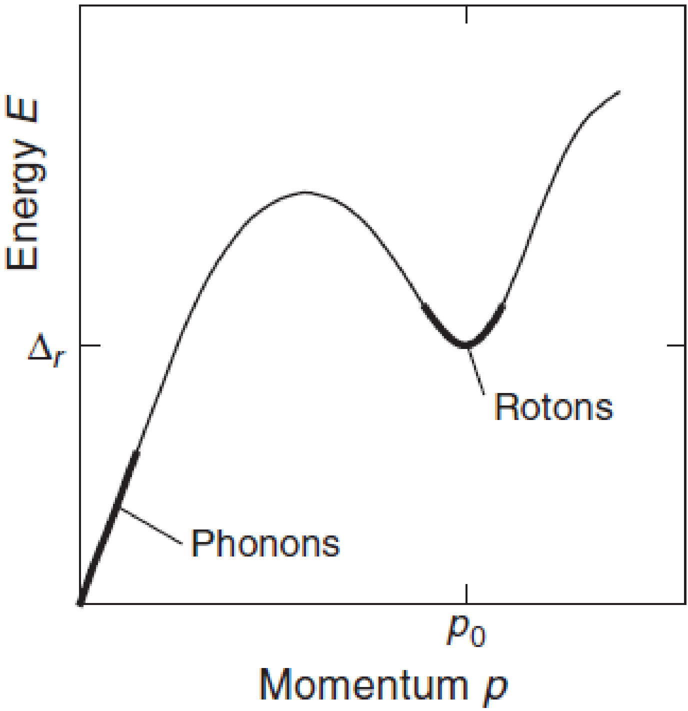


- B.E.C. model predicts 100% of fluid becomes superfluid at T=0.
- Experiments measure around 14%
- Data in plot: neutron diffraction, electron scattering. Dotted line: surface tension. Line: empirical fit



Excitations in He II

- No interactions in ideal Bose gas
- There ARE interactions is He II
- This explains the failures of the B.E.C. model
- Landau (1941): He II has only collective excitations; individual atom excitations are suppressed – success in explaining many of the features we saw
- Collective excitations crucial for superfluid behaviour
- Two types of thermally excited modes: phonons and rotons



(or wavenumber)